CHAPTER 7

CULVERT RETROFIT DESIGN

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7 CULVERT RETROFIT DESIGN

7.1 Design Method Applicability

The most effective solution for improving fish passage through an existing culvert is to replace it with a new structure designed using relevant fish passage design criteria. However, there are cases in which culvert replacement is difficult to justify, such as when the existing culvert is relatively new and has a significant remaining design life, or when there are plans to replace the culvert 5 or 10 years in the future as part of other planned roadway improvements. In such cases, a decision may be made to improve fish passage through the existing culvert to the extent possible, using culvert retrofit methods as described in this chapter.

When selecting a method for retrofitting a culvert to improve fish passage, the first step is to determine why the culvert is a fish passage barrier. If flow depths are too shallow in the culvert barrel, then baffles or weirs may need to be installed to create small pools (Figure 7-1a). If flow velocities are too high through the length of the barrel, then baffles may provide additional roughness and turbulence that disperses some of the excess energy (Figure 7-1b). In some cases, baffles can serve both functions, increasing flow depth during low flow conditions and reducing velocities under higher flow conditions.

a)

b)

Figure 7-1. Applications for the use of culvert retrofit design include a) adding depth and b) adding roughness. (Photos courtesy of WDFW)

In some cases, poor passage conditions in the barrel may be further mitigated by increasing the level of the tailwater at the culvert outlet, using grade control structures such as rock weirs. Grade control techniques are also used if the culvert outlet is elevated above the water surface of the stream, due to original design intent or due to channel erosion or degradation occurring since original culvert installation. The design of grade control structures is addressed in Chapter 8. In extreme cases when the culvert outlet is several feet above the water surface of the stream, a fishway may need to be constructed at the downstream end of the culvert to allow fish to enter the culvert. An overview of fishway design methods is presented in Chapter 9.

In engineering literature, the term “weir” is commonly applied to structures that divert the flow or control the level of a waterway. A “baffle” is a device used to control or impede the flow of something and reduce its force. When a structure is designed to serve as a weir within a culvert, it may act more as a baffle once it is submerged, and conversely a structure designed to serve as a submerged baffle may effectively become a weir under low flow conditions. In this chapter, an effort is made to use the precise term when it is important to distinguish the function or the design approach for the structure. In more general discussions, however, the terms may be used interchangeably as a means to avoid repetitive listings of the two types of structures.

Figure 7-2 shows two views of a culvert retrofit project completed at Crooked Creek in Mono County, California. The left photo shows a longitudinal weir installed through the length of the flat bottom culvert to narrow the low flows and increase depth for fish passage. The right photo shows concreted rock weirs at the outlet end that provide a stepped pool transition to the stream below. Additional detail regarding the Crooked Creek project is included with other Caltrans projects presented in Appendix I of this manual.

Figure 7-2. Longitudinal channel weir and grade control rock weirs at the Crooked Creek retrofit project.

7.1.1 Retrofit Limitations

In the fisheries community, there is considerable debate as to whether baffled culverts are effective at improving fish passage on a long-term basis. A baffled culvert clogged with sediment or debris may temporarily reduce the fish passage effectiveness in comparison to the original open-barrel configuration (Figure 7-3a). Baffles installed with insufficient anchoring may dislodge during flood events and make the debris situation even worse (Figure 7-3b). Sites being evaluated for potential retrofit action that have high debris loading should give strong consideration to NOT construct baffles. Similarly, if there is a high degree of uncertainty as to whether there is available hydraulic capacity in the culvert, it may be better to reject any consideration of baffles.

a) debris caught on baffle

b) failure due to insufficient anchoring

Figure 7-3. Baffles can contribute to passage problems. (Photos courtesy of WDFW)

The following situations describe some of the potential limitations of a culvert retrofit that should be considered during the design process:

- Any obstruction inside a culvert, including baffles and weirs, generates the potential for accumulation of debris and sediment. Weirs constructed with sharp edges and Vs, in particular, will tend to trap organic matter. In general, the lower and smoother the weir, the lower the potential for debris accumulation.
- The space occupied by the baffles or weirs, in conjunction with debris and sediment accumulation, can significantly reduce the flow capacity of the culvert.
- Baffles should generally not be considered for circular culverts less than 3.6" in diameter, due to difficulties accessing the culvert interior for installation and maintenance.
- The design life of baffles is typically substantially less than for a new culvert. As a result, baffles may have to be replaced during the remaining life of the culvert. (At the same time, a factor that leads to baffle installation is frequently that the culvert is nearing the end of its design life, and the baffles are intended to enhance passage during the interim period until the culvert is replaced.)
- Baffled facilities will generally require more frequent monitoring and maintenance than open-barrel culverts. These increased costs should be included in any analysis of the life-cycle costs of the retrofit.

7.1.2 Research and Understanding of Baffled Culverts

Extensive laboratory studies conducted by Shoemaker (1956) examined flow conditions in baffled box culverts, and Rajaratnam and Katapodis (1989, 1990) examined flow conditions for three styles of baffled circular culverts: offset weirs, slotted weirs, and weir baffles These studies provide methods for estimating average depth and average velocity in baffled culverts having similar design. See Appendix F for more information concerning the baffle weir research conducted by Rajaratnam and Katapodis.

More recently, several entities have completed field evaluations of existing baffled culvert installations (Browning 1990, OSU and ODOT in press, WDFW in press). These observations have led to the development of practical guidelines for baffle design and installation. These guidelines are described in Section 7.2.

The following bulleted items identify key issues relating to the design of baffled culverts.

- The methods for estimating average depth and average velocity are empirical methods based on measurements of flow conditions in baffled culverts having specific conditions for baffle height, baffle spacing, and culvert slope.
- Use of these methods to estimate water depth and velocity in culverts having other styles of baffles should be viewed with caution.
- The studies measured considerable range of velocities occurring within the baffled culverts. Areas of lowest velocity tend to occur near the side walls and along the upstream faces of the baffles.
- Field observations of fish movement through baffled culverts suggest fish tend to move through the zones of lower velocity, especially for juveniles and weaker swimming fishes (Behlke et al. 1991, OSU and ODOT in press, Powers 2000).
- Many engineers and fish biologists hold the strong opinion that design of baffled culverts should not be based on the same average velocity criteria as for open barrel culverts, as the fish movement occurs in zones of much lower velocity not evident in the average velocity calculation.
- Calculation methods developed to date are applicable only up to flow depths of approximately 0.9 D. Estimates for baffled culverts flowing full are highly speculative at present.

For additional background information regarding the hydraulics of baffled culverts, the reader can refer to Appendix F.

7.2 Retrofit Design Methods

7.2.1 Tailwater Control Weirs

Weirs located at the downstream end of an existing culvert are typically used to eliminate hydraulic drops at the outfall of the culvert. Additionally, tailwater control weirs are also used to increase flow depths in the culvert during periods of low flow to facilitate fish passage. Depending on the length and slope of the culvert and the height of the downstream weir, improvements can be realized for all or just a portion of the culvert.

Tailwater control weirs offer an advantage over baffles in that they are located outside the culvert barrel. Due to the more open expanse of a tailwater control weir, they are likely to exhibit lower risk of severe debris jamming than might occur with baffle weirs located inside the culvert barrel. In cases where debris jams occur, the maintenance requirement is likely to be more easily accomplished at the exterior tailwater control weir. As a first step in any retrofit design, it is strongly recommended that tailwater control weirs be evaluated first to determine whether they can accomplish the fish passage remediation without the need for baffles. Chapter 8 provides more information regarding the design of tailwater control weirs and other grade control measures to facilitate fish passage.

7.2.2 Baffles

Baffles can be installed in culverts to function primarily as weirs to increase flow depth, or to add roughness elements as a measure to reduce flow velocity. Regardless of their functional objective, it is important to recognize that baffles will exhibit different flow characteristic under low and high flow conditions. During low flow conditions, baffles will exhibit a step-pool effect with plunging flow characteristics. During high flow conditions, there will be streaming flow characteristics occurring in the flow above the baffle crests, while "hydraulic shadows" are created at the downstream face of the baffles (Figure 7-5).

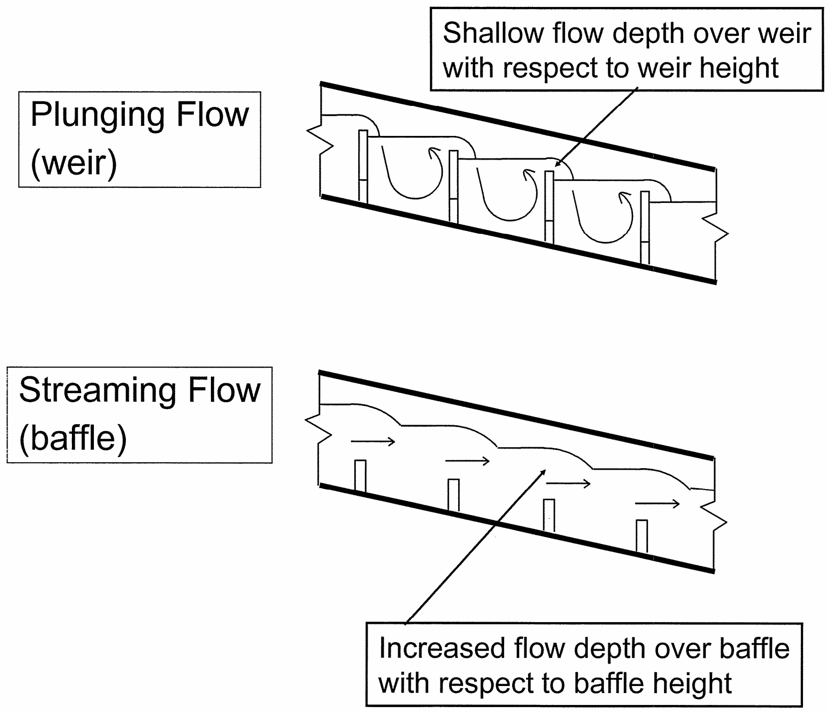

Figure 7-4. Baffles will exhibit plunging flow or streaming flow characteristics depending on the flow depth over the baffles. (WDFW in press)

Several entities have completed performance evaluations of baffled culvert installations and have summarized the findings as a means to provide design guidance for future projects (OSU and ODOT in press, Powers 2000). The WDFW evaluation (Powers 2000) investigated the use of baffles and their impact to Manning's roughness coefficient for culverts with slopes less than 3.5%. Based on these findings, WDFW had developed a methodology for evaluating the presence of baffles inside the culvert. There is a simplicity of this method that rests on the fact that only the value for Manning's roughness is changed in Manning's equation. This allows the designer to use standard tools (e.g. Manning's calculators, software programs, and hydraulic elements tables) to be used in design.

Table 7-1 presents the Manning's roughness values (n) recommended by WDFW (Powers 2000) in their baffled culvert design. The n value is dependent on the configuration of the weir.

Table 7-1. WDFW Baffle Design Guidelines

Culvert Slope (ft/ft)	Baffle Height, Z_0 (inch)	Baffle Spacing, L (ft)	Manning's n
0.005 to 0.009	6 to 8	0.10/slope	0.04 to 0.05
0.010 to 0.024	8 to 10	0.15/slope	0.06 to 0.07
0.025 to 0.035	10 to 12	0.20/slope	0.08 to 0.09

A first step to baffle design is to develop a preliminary baffle configuration and spacing.

Because of the potential for excessive turbulence inside a culvert, it is recommended that baffles have a minimum spacing of 6 feet. For a given culvert site, the baffle spacing will also be influenced by baffle height, culvert slope, and Manning's roughness. These variables, of course, will be adjusted during the hydraulics analysis in order to meet, or nearly meet, the fish-passage criteria under the Hydraulic Design option. Using the recommended value for Manning's n, normal flow depth (y_o) can be estimated for low fish passage flows and velocity (V) can be determined at high fish passage flows. For this analysis, the entire flow area is assumed available and is not reduced to account for the presence of the baffles. Based on the results of the preliminary analysis, the baffle configuration should be modified to meet the fish passage criteria for normal flow depth and velocity. Additionally, WDFW recommends that the ratio of the baffle height to the normal flow depth (Z_o/y_o) be between 0.4 and 0.6.

7.2.2.1 Box Culvert Installations

Based on several years of testing and evaluation (OSU and ODOT in press), ODOT has achieved a high level of success in using baffles to enhance fish passage conditions in concrete box culverts. These installations commonly focus on using the baffles to increase flow depth, as the broad, flat beds of box culverts are likely to require significant discharges before achieving the 6 inch to 12 inch minimum flow depths required by fish passage criteria. Added advantages of box culvert retrofits over circular or arch retrofits include the lower rate of change in HW/D response as the headwater approaches the soffit, thereby suggesting greater tolerance to the displaced hydraulic capacities resulting from the baffle cross-sectional area. Box culverts are also less likely to have debris problems than circular or arch culvert having equal width.

For box culverts having a slope less than 2.5%, ODOT has found the flow characteristics to be most effective when the baffle is angled at 30 relative to the wall. When the slope is greater than 3%, a full width weir baffle may be used to enhance the step-pool affect (Figure 7-6). Spacing between the baffles is determined by the slope, the minimum depth requirements, and the selected baffle height. A baffle height of 8' is commonly used, but in cases with higher slopes and if there is substantial excess hydraulic capacity, a 12' baffle will be evaluated. To accommodate the turbulence that occurs due to flow constriction at the inlet, ODOT typically places the uppermost baffle no closer than 12' to the inlet.

A low flow notch is desirable in either the mild or steep configuration. For mild culverts, the notch is commonly formed by the gap between the end of the angled baffle and the wall, and the gap size is set by determining the width which provides the minimum flow depth at the low fish passage flow. For steeper slopes having a full span baffle weir, it is common to provide a notch that is 300 to 600 mm wide and 25 to 50 mm lower than the baffle crest (Figure 7-7).

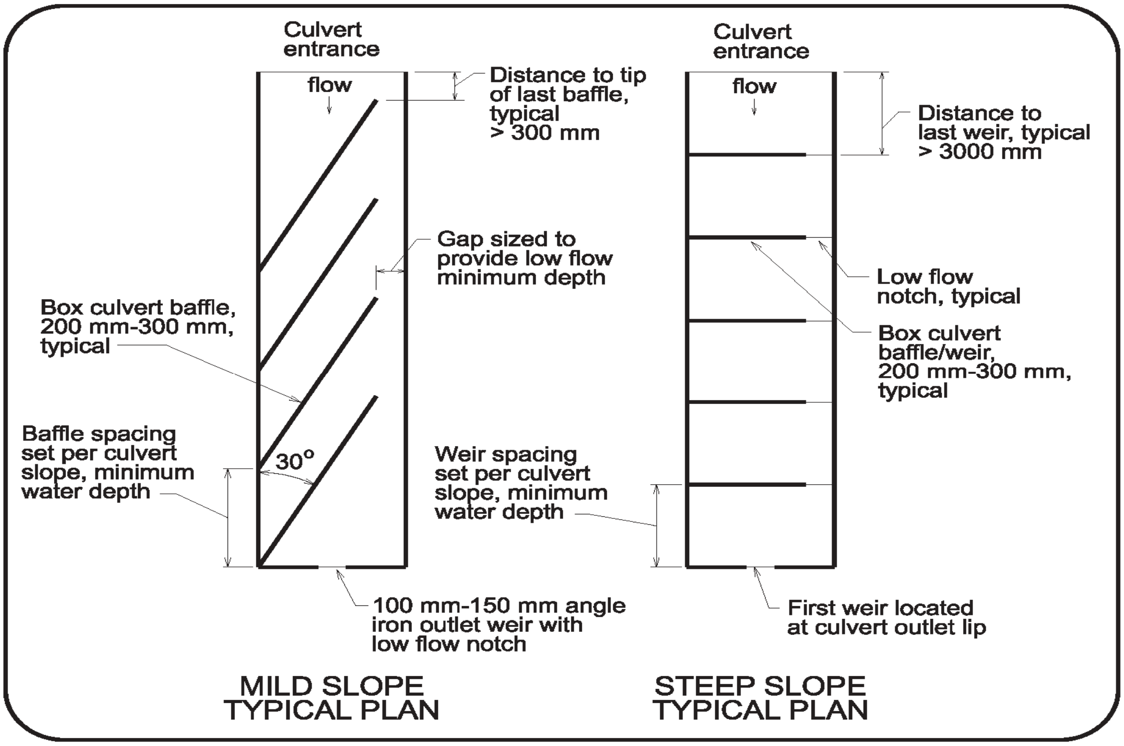

Figure 7-5. Typical plans for baffled box culverts on mild and steep slopes. (Adapted from ODOT)

Figure 7-6. Baffle weirs spanning a steep-slope box culvert. (Photos courtesy of ODOT)

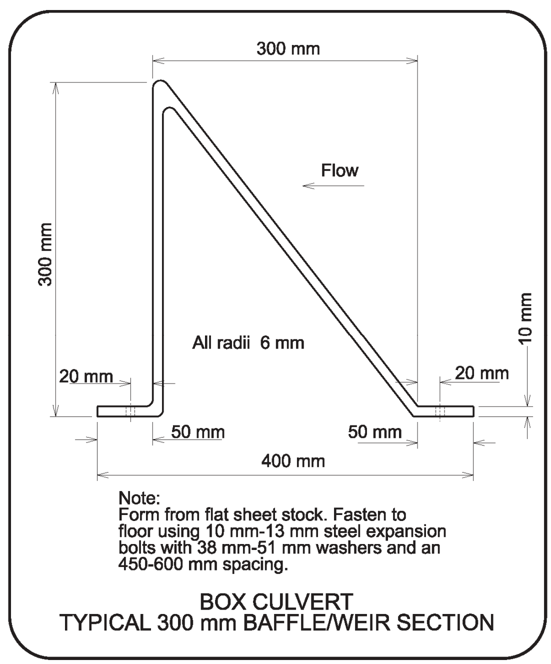

Figure 7-7. Section of standard 300 mm box culvert baffle/weir. (Adapted from ODOT)

ODOT has found that the success of the retrofit often relates to the ability to provide good entrance conditions below the culvert. A weir is always placed at the downstream edge of the culvert. When the apron has flared edges, ODOT has found it effective to provide low level concrete weirs from the outlet of the culvert extending to the end or the apron, to promote the same flow vectors as occur inside the culvert under low flow conditions (Figure 7-9). A metal sill with a low flow notch is placed at the edge of the apron to maintain the flow depth on the apron. Since these efforts to concentrate the flows under low flow conditions can produce relatively high velocities as the discharge increases, a second entrance is sometimes provided on the flared segment of the apron, supplied by a notch in the training wall (Figure 7-9).

Figure 7-8. Enhancements at box culvert outlets might include training walls and notched weir sills to maintain flow depth in the main channel section, along with secondary entrances to promote better conditions for juveniles during higher flow conditions. (Photo courtesy of ODOT)

7.2.2.2 Circular Pipe Installations

Baffles in circular pipes are commonly angled to one side, both to promote passage of debris as well as to create a low flow notch under the lowest flow conditions (Figure 7-10a). Typical dimensions for baffles of this type are included in Appendix J. In cases where the main objective is to add roughness, but at the same time there is concern regarding bedload or debris accumulation, it may be effective to position the baffles on the side of the culvert (Figure 7-10b).

Expansion-ring anchors work well in round pipes and can be installed without diverting flow from the work area. The rings are expanded out against the entire pipe circumference. A rod is rolled to the shape of the culvert interior and attached to an anchor plate. The rod and anchor plate are attached to the culvert by expanding the rod into the recess of a corrugation. This is done by tightening a nut on one end of the rod against a sleeve attached to the other end of the rod. Once the rod and anchor plate are secured, the baffle is bolted to the anchor plate. This system will also work in smooth culverts. A set of shear bolts must first be anchored to the culvert wall; the expansion ring is then installed against the upstream side of the shear bolts. An example sketch of an expansion ring anchor is included in Appendix J.

a) b)

Figure 7-9. Baffles in circular pipe culverts are most commonly positioned in the "corner", but can also be placed on the side. (Photos courtesy of Caltrans and ODOT)

7.2.3 Roughened Channel within Culvert

Flow depths can be increased and average culvert velocities can be reduced through the introduction of bed material on the interior of the culvert. This process involves placing hydraulically stable material inside the culvert. This method requires considerable hydraulic engineering expertise, and the District Hydraulic Unit should be contacted early in the preliminary design stage if this design option is to be evaluated.

7.3 Retrofit Design Process Overview

The design process for culvert retrofits consists of several basic elements, as shown in the list below. The broader design components as shown in the list are discussed in the following sections of this chapter. See Appendix M for a culvert retrofit design example.

1. Collect engineering data.
    - Confirm the maximum allowable headwater elevation.
    - Determine outlet pool and tailwater conditions
    - Determine the maximum acceptable 100-year flood discharge velocity for stability of the existing channel.
2. Identify the retrofit culvert design criteria.
3. Complete the design flow determinations for high fish passage flow, low fish passage flow, and 100-year flow.
4. Enter data regarding the culvert configuration being analyzed. (The existing conditions for the culvert and channel are used for the first iteration.)
5. Conduct the hydraulic analysis.
    - Identify flow depths and average velocities in the culvert at the high and low fish passage flows and compare to the limiting values.

- Compute the 100-year discharge velocity and headwater depth and compare to the limiting value.

6. Evaluate the tailwater condition (i.e. develop a tailwater rating curve). Adjust tailwater configuration as needed through grade control measures. (Refer to Chapter 8 for guidance on grade control design.) Return to Step 4 unless no further tailwater adjustments are required.
7. Evaluate the barrel condition. Adjust configuration as needed by adding baffles. Return to Step 4 unless no further baffle adjustments are required.
8. Repeat steps 4 through 7 until the optimal configuration is identified.

The sequence for completing the first three steps can vary to some extent, as these steps include data collection and assessment activities that in some cases are independent of one another. Steps 4 through 8 reflect the iterative process that conducts the hydraulic analyses and optimizes the design.

7.4 Retrofit Design Elements

7.4.1 Data Collection

7.4.1.1 Existing Culvert Design Records

Many (but not all) of the culverts that become the subject of a Caltrans retrofit project should have documentation relating to their original design and installation. These documents should be reviewed initially to determine the extent of the information and to identify key design criteria used for the original design. While this information may provide insights in to the original design, none of the existing information should be used directly without a) completing a field verification of the existing condition of relevant items and b) reviewing the accuracy and current applicability of the methods and calculations used for design. Examples of existing culvert design data that should be obtained and verified include:

- Culvert length
- Culvert slope. Field assessment should investigate the presence of any settling or sagging within the culvert.
- Culvert diameter (or other relevant dimensions for non-circular culverts). Field assessment should investigate the presence of embedment material and any warping within the culvert.
- Culvert material and current condition of roughness. The depth and spacing of pipe corrugations should be verified when present.
- Culvert basin information, including any assumptions regarding land cover and developed area within the basin.
- The calculated or assumed elevation for allowable headwater.
- Calculated outlet velocity and assumptions used in designing slope protection, where present.

7.4.1.2 Site Assessment Data

Existing conditions at the project site must be assessed and, where appropriate, compared to conditions described for the original design. Prior to conducting field visits, it will be beneficial to review existing fish passage evaluations that may have been completed previously; the designer should check for their existence with the District Environmental Unit and obtain copies if available.

See Chapter 3 for guidance regarding data collection for the following items:

- Channel Topography
- Channel Stability
- Acceptable Outlet Velocity

7.4.1.3 Fish Passage Criteria

Fish passage criteria described by CDFG (2002) and NOAA-SWR (2001) classify culvert retrofit projects under the Hydraulic Design Option category. The fish passage criteria for this option require identification of the target species. Contact the District Environmental Unit early in the preliminary design stage if there is any uncertainty regarding the target species for a specific project.

Criteria for the Hydraulic Design Option also specify the methods for determining the low fish passage flow rate and high fish passage flow rate. The CDFG criteria are shown in Appendix B and the NOAA-SWR criteria are shown in Appendix C.

For a culvert retrofit project, however, it is recognized that velocity conditions within the existing culvert barrel may not be capable of being modified to the extent that would satisfy maximum average water velocity criteria used for new and replacement culverts. It is recognized that, in some cases, fish passage can be significantly improved for some species and life stages without fully meeting the hydraulic criteria. Therefore, for culvert retrofit projects, both CDFG (2002) and NOAA-SWR (2001) suggest that the same maximum average water velocity criteria used for new and replacements culverts should serve as the target for passage improvement and not the required design threshold. The velocity criteria are shown in Appendices B and C.

The existing conditions of a culvert retrofit project are unlikely to allow any significant reduction in the headwater level exhibited during the 100-year peak flood flow. As a result, if the HW/D ratio of the existing culvert is greater than 1.5, there is little likelihood of satisfying the CDFG criterion stating that the upstream water surface depth above the top of the culvert inlet for the 100-year peak flood shall not be greater than 50 percent of the culvert rise. Similar to the criterion for the maximum average water velocity, the HW/D criterion is generally considered a target for passage improvement and not the required design threshold.

7.4.2 Hydrologic Analysis

A hydrologic analysis needs to be performed using methodologies outlined in Chapter 3. As outlined in the fish passage criteria (CDFG 2002, NOAA-SWR 2001), design flows for high fish passage flow can be determined using either the Annual Exceedance Flow (AEF) or a percentage of the 2-year recurrence interval flow (Q2). If detailed stream records are available at the project area, the determination of AEF may be appropriate. However, in most cases flow records will not be available, in which case it will be necessary to determine the Q2 through other methods.

7.4.3 Hydraulic Analyses

Use of the hydraulic design option for culvert retrofit projects requires that hydraulic analyses be completed to assess water depths, drops in the water surface profile, and flow velocities in the culvert and the adjacent channel, and to determine the headwater elevation at the culvert entrance. Several types of hydraulic design methods are acceptable for these determinations, varying in their complexity and level of accuracy. Section 3.X provides a review of the basic hydraulic concepts that are encountered with culvert operations, and it discusses the more common design methods and computer programs that are used in the culvert design process. Throughout the remainder of this chapter, the discussion will use the terminology and typical procedures and results that follow from use of the HEC-RAS computer program.

The general approach for designing retrofit facilities is an iterative process. For a culvert retrofit, the first iteration will provide an analysis of conditions in the existing culvert. An analysis of an existing culvert using the HEC-RAS program typically requires an initial data input session providing data sets similar to the following:

- Data regarding the existing culvert configuration: culvert inverts, stationing, size, shape, material, roughness, entrance type
- Data relating to the tailwater conditions: channel cross section data; observed water surface elevations for a minimum of three specific discharge conditions
- Data regarding overtopping conditions
- Identification of the design flow discharges for which analyses will be provided

When data input is complete, the designer directs the HEC-RAS program to conduct the hydraulic analysis. The typical output from the program is a listing of 10 discharge flows (in addition to the no flow condition) that additionally itemizes the following associated conditions for each flow: headwater elevation, inlet and outlet control depth, flow type, normal depth, critical depth, outlet depth, tailwater depth, outlet velocity, and tailwater velocity.

At this point, results from the analysis are compared to design criteria limits. As an example, the normal depth of flow associated with the low fish passage flow will provide a determination as to whether the minimum depth criterion is satisfied in the existing culvert.

If adjustments are necessary, analyze adjusted configurations until an acceptable design is found.

7.4.4 Retrofit Features Design

The design of retrofit features will be dependent on several factors, including the effectiveness of tailwater control measures; whether the culvert is a box culvert or circular / arch culvert; the slope of the culvert; and the bedload and debris conditions. See Section 7.2 for guidance on design of the baffle features.